

Open flavor strong decays

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In this contribution, we discuss the results of a QM calculation of the open-flavor strong decays of **** light nucleon resonances. These are the results of a recent calculation, where we used a modified 3P_0 model for the amplitudes and the $U(7)$ algebraic model and the Hypercentral Quark Model to predict the baryon spectrum. The decay amplitudes are compared with the existing experimental data.

I. INTRODUCTION

The study of the strong decay processes of baryons is still considered a challenge within theoretical and experimental hadronic physics. At the moment, the number of known light-quark mesons is much larger than the number of known baryon resonances [1]. However, it is known that the baryon spectrum is much more complex than the meson one. The difficulty lies in identifying those high-lying baryon resonances that are only weakly coupled to the $N\pi$ channel [2, 3] and thus cannot be seen in elastic $N\pi$ scattering experiments.

Regarding the strong decays of baryon resonances, no satisfactory description has yet been achieved. We could list several problems as, for example, the QCD mechanism behind the OZI-allowed strong decays [4], which is still not clear. Theoretical calculations of baryon strong, electromagnetic and weak decays still help the experimentalists in their search of those resonances that are still unknown, even if interesting results were provided by CB-ELSA [5], TAPS [6], GRAAL [7], SAPHIR [8] and CLAS [9].

Several phenomenological models have been developed in order to carry out strong decay studies, including pair-creation models [10–17], elementary meson emission models [18–23] and effective Lagrangian approaches (for example, see Ref. [24]). A few years after the introduction of the 3P_0 model [10], Le Yaouanc *et al.* used it to compute meson and baryon open flavor strong decays [11] and also evaluated the strong decay widths of charmonium states [25]. The 3P_0 model, extensively applied to the decays of light mesons and baryons [26], has been recently applied to heavy meson strong decays, in the charmonium [27–29], bottomonium [29, 30] and open charm [31, 32] sectors. In the 90’s, Capstick and Roberts calculated the $N\pi$ and the strange decays of nonstrange baryons [3], using relativized wave functions for the baryons and mesons.

Recently, we have computed the decay widths of baryon resonances into baryon-pseudoscalar meson pairs [33] within a modified 3P_0 model, using two different models for the mass spectrum: the $U(7)$ algebraic model [34, 35], by Bijker, Iachello and Leviatan, and the hypercentral model (hQM) [36], developed by Giannini and Santopinto. The widths have been computed with harmonic oscillator wave functions. In this contribution, we discuss our main results for the two-body strong decay widths of **** nucleon resonances.

II. $U(7)$ MODEL FOR BARYONS

The baryon spectrum is computed by means of algebraic methods introduced by Bijker, Iachello and Leviatan [34, 35]. The algebraic structure of the model consists in combining the symmetry of the internal spin-flavor-color part, $SU_{sf}(6) \otimes SU_c(3)$, with that of the spatial part, $U(7)$ into

$$U(7) \otimes SU_{sf}(6) \otimes SU_c(3) . \quad (1)$$

The $U(7)$ model was introduced [34] to describe the relative motion of the three constituent parts of the baryon. The general idea is to introduce a so-called spectrum generating algebra $U(k+1)$ for quantum systems characterized

by k degrees of freedom. For baryons there are the $k = 6$ relevant degrees of freedom of the two relative Jacobi vectors $\vec{\rho} = \frac{1}{\sqrt{2}}(\vec{r}_1 - \vec{r}_2)$ and $\vec{\lambda} = \frac{1}{\sqrt{6}}(\vec{r}_1 + \vec{r}_2 - 2\vec{r}_3)$ and their canonically conjugate momenta, $\vec{P}_\rho = \frac{1}{\sqrt{2}}(\vec{p}_1 - \vec{p}_2)$ and $\vec{P}_\lambda = \frac{1}{\sqrt{6}}(\vec{p}_1 + \vec{p}_2 - 2\vec{p}_3)$. The $U(7)$ model is based on a bosonic quantization which consists in introducing two vector boson operators b_ρ^\dagger and b_λ^\dagger associated to the Jacobi vectors, and an additional auxiliary scalar boson, s^\dagger . The scalar boson does not represent an independent degree of freedom, but is added under the restriction that the total number of bosons N is conserved. The model space consists of harmonic oscillator shells with $n = 0, 1, \dots, N$.

The baryon mass formula is written as the sum of three terms

$$\hat{M}^2 = M_0^2 + \hat{M}_{\text{space}}^2 + \hat{M}_{\text{sf}}^2, \quad (2)$$

where M_0^2 is a constant, \hat{M}_{space}^2 is a function of the spatial degrees of freedom and \hat{M}_{sf}^2 depends on the internal ones. The spin-flavor part is treated in the same way as in Ref. [35] in terms of a generalized Gürsey-Radicati formula [37], which in turn is a generalization of the Gell-Mann-Okubo mass formula [38, 39].

Since the space-spin-flavor wave function is symmetric under the permutation group S_3 of three identical constituents, the permutation symmetry of the spatial wave function has to be the same as that of the spin-flavor part. Thus, the spatial part of the mass operator \hat{M}_{space}^2 has to be invariant under the S_3 permutation symmetry. The dependence of the mass spectrum on the spatial degrees of freedom is given by:

$$\hat{M}_{\text{space}}^2 = \hat{M}_{\text{vib}}^2 + \hat{M}_{\text{rot}}^2. \quad (3)$$

The baryon wave functions are denoted in the standard form as

$$|^{2S+1}\text{dim}\{SU_f(3)\}_J [\text{dim}\{SU_{sf}(6)\}, L_i^P] \rangle, \quad (4)$$

where S and J are the spin and total angular momentum $\vec{J} = \vec{L} + \vec{S}$. As an example, in this notation the nucleon and delta wave functions are given by $|^28_{1/2}[56, 0_1^+]\rangle$ and $|^410_{3/2}[56, 0_1^+]\rangle$, respectively.

III. HQM FOR BARYONS

In the hQM is supposed that the quark interaction is hypercentral, namely it only depends on the hyperradius [36, 40],

$$V_{3q}(\vec{\rho}, \vec{\lambda}) = V(x), \quad (5)$$

where $x = \sqrt{\vec{\rho}^2 + \vec{\lambda}^2}$ is the hyperradius [41]. Thus, the space part of the three quark wave function, ψ_{space} , is factorized as

$$\psi_{\text{space}} = \psi_{3q}(\vec{\rho}, \vec{\lambda}) = \psi_{\gamma\nu}(x) Y_{[\gamma]l_\rho l_\lambda}(\Omega_\rho, \Omega_\lambda, \xi), \quad (6)$$

where the hyperradial wave function, $\psi_{\gamma\nu}(x)$, is labeled by the grand angular quantum number γ and the number of nodes ν . $Y_{[\gamma]l_\rho l_\lambda}(\Omega_\rho, \Omega_\lambda, \xi)$ are the hyperspherical harmonics, with angles $\Omega_\rho = (\theta_\rho, \phi_\rho)$, $\Omega_\lambda = (\theta_\lambda, \phi_\lambda)$ and hyperangle, $\xi = \arctan \frac{\rho}{\lambda}$ [41]. The dynamics is contained in $\psi_{\gamma\nu}(x)$, which is a solution of the hyperradial equation

$$\left[\frac{d^2}{dx^2} + \frac{5}{x} \frac{d}{dx} - \frac{\gamma(\gamma+4)}{x^2} \right] \psi_{\gamma\nu}(x) = -2m [E - V_{3q}(x)] \psi_{\gamma\nu}(x). \quad (7)$$

In the hQM, the quark interaction has the form [36, 40]

$$V(x) = -\frac{\tau}{x} + \alpha x, \quad (8)$$

where τ and α are free parameters, fitted to the reproduction of the experimental data. Eq. (8) can be seen as the hypercentral approximation of a Cornell-type quark interaction [12], whose form can be reproduced by Lattice QCD calculations [42]. Now, to introduce splittings within the $SU(6)$ multiplets, an $SU(6)$ -breaking term must be added. In the case of the hQM, such violation of the $SU(6)$ symmetry is provided by the hyperfine interaction [43, 44]. The complete hQM hamiltonian is then [36, 40]

$$H_{\text{hQM}} = 3m + \frac{\vec{p}_\rho^2}{2m} + \frac{\vec{p}_\lambda^2}{2m} - \frac{\tau}{x} + \alpha x + H_{\text{hyp}}, \quad (9)$$

where \vec{p}_ρ and \vec{p}_λ are the momenta conjugated to the Jacobi coordinates $\vec{\rho}$ and $\vec{\lambda}$. In addition to τ and α , there are two more free parameters in the hQM, the constituent quark mass, m , and the strength of the hyperfine interaction. The former is taken, as usual, as 1/3 of the nucleon mass. The latter, as in the case of τ and α , is fitted in [36] to the reproduction of the *** and **** resonances reported in the PDG [1].

TABLE I: The select strong decay widths of **** nucleon resonances (in MeV) from Ref.[33] . The spectrum is computed using the U(7) Model of Sec. II and Refs. [34, 35] and Hypercentral QM of Sec. III and Refs. [36, 40], in combination with the relativistic phase space factor of Eq. (11) and the values of the model parameters of Table II (second column). The experimental values are taken from Ref. [1]. Decay channels labeled by – are below threshold. The symbols (S) and (D) stand for S and D-wave decays, respectively.

Resonance	Status	M [MeV]	$N\pi$	$N\eta$	ΣK	ΛK	$\Delta\pi$	
$N(1440)P_{11}$	****	1430-1470	110 – 338	0 – 5			22 – 101	Exp.
$^2_{8_{1/2}}[56, 0_2^+]$		1444	85	–	–	–	13	U(7)
$^2_{8_{1/2}}[56, 0_2^+]$		1550	105	–	–	–	12	hQM
$N(1520)D_{13}$	****	1515-1530	102	0			342	Exp.
$^2_{8_{3/2}}[70, 1_1^-]$		1563	134	0	–	–	207	U(7)
$^2_{8_{3/2}}[70, 1_1^-]$		1525	111	0	–	–	206	hQM
$N(1535)S_{11}$	****	1520-1555	44 – 96	40 – 91			< 2	Exp.
$^2_{8_{1/2}}[70, 1_1^-]$		1563	63	75	–	–	16	U(7)
$^2_{8_{1/2}}[70, 1_1^-]$		1525	84	50	–	–	6	hQM
$N(1650)S_{11}$	****	1640-1680	60 – 162	6 – 27		4 – 20	0 – 45	Exp.
$^4_{8_{1/2}}[70, 1_1^-]$		1683	41	72	–	0	18	U(7)
$^2_{8_{1/2}}[70, 1_2^-]$		1574	51	29	–	0	4	hQM
$N(1675)D_{15}$	****	1670-1685	46 – 74	0 – 2		< 2	65 – 99	Exp.
$^4_{8_{5/2}}[70, 1_1^-]$		1683	47	11	–	0	108	U(7)
$^4_{8_{5/2}}[70, 1_1^-]$		1579	41	9	–	–	85	hQM
$N(1680)F_{15}$	****	1675-1690	78 – 98	0 – 1			6 – 21	Exp.
$^2_{8_{5/2}}[56, 2_1^+]$		1737	121	1	–	0	100	U(7)
$^2_{8_{5/2}}[56, 2_1^+]$		1798	91	0	0	0	92	hQM

IV. TWO-BODY STRONG DECAYS OF LIGHT NUCLEON RESONANCES IN THE 3P_0 PAIR-CREATION MODEL

Here, we present some our results for the two-body strong decay widths of nucleon resonances in the 3P_0 pair-creation model. The decay widths are computed as [10, 11, 17, 27, 28, 30, 33, 45]

$$\Gamma_{A \rightarrow BC} = \Phi_{A \rightarrow BC}(q_0) \sum_{\ell, J} |\langle BC \vec{q}_0 \ell J | T^\dagger | A \rangle|^2, \quad (10)$$

where, $\Phi_{A \rightarrow BC}(q_0)$ is the relativistic phase space factor:

$$\Phi_{A \rightarrow BC}(q_0) = 2\pi q_0 \frac{E_b(q_0)E_c(q_0)}{M_a}, \quad (11)$$

depending on q_0 and on the energies of the two intermediate state hadrons, $E_b = \sqrt{M_b^2 + q_0^2}$ and $E_c = \sqrt{M_c^2 + q_0^2}$. We assumed harmonic oscillator wave functions, depending on a single oscillator parameter α_b for the baryons and α_m for the mesons. The coupling between the final state hadrons $|B\rangle$ and $|C\rangle$ is described in terms of a spherical basis [33]. Specifically, the final state $|BC \vec{q}_0 \ell J\rangle$ can be written as

$$\begin{aligned} |BC \vec{q}_0 \ell J\rangle &= \sum_{m, M_b, M_c} \langle J_b M_b J_c M_c | J_{bc} M_{bc} \rangle \\ &\quad \langle J_{bc} M_{bc} \ell m | J M \rangle \frac{Y_{\ell m}(\hat{q})}{q^2} \delta(q - q_0) \\ &\quad |(S_b, L_b) J_b M_b\rangle |(S_c, L_c) J_c M_c\rangle, \end{aligned} \quad (12)$$

where the ket $|BC \vec{q}_0 \ell J\rangle$ is characterized by a relative orbital angular momentum ℓ between B and C and a total angular momentum $\vec{J} = \vec{J}_b + \vec{J}_c + \vec{\ell}$.

The transition operator of the 3P_0 model is given by [28, 30, 33, 45]:

$$T^\dagger = -3\gamma_0^{\text{eff}} \int d\vec{p}_4 d\vec{p}_5 \delta(\vec{p}_4 + \vec{p}_5) C_{45} F_{45} e^{-r_q^2(\vec{p}_4 - \vec{p}_5)^2/6} [\chi_{45} \times \mathcal{Y}_1(\vec{p}_4 - \vec{p}_5)]_0^{(0)} b_4^\dagger(\vec{p}_4) d_5^\dagger(\vec{p}_5). \quad (13)$$

Here, $b_4^\dagger(\vec{p}_4)$ and $d_5^\dagger(\vec{p}_5)$ are the creation operators for a quark and an antiquark with momenta \vec{p}_4 and \vec{p}_5 , respectively. The $q\bar{q}$ pair is characterized by a color singlet wave function C_{45} , a flavor singlet wave function F_{45} , a spin triplet wave function χ_{45} with spin $S = 1$ and a solid spherical harmonic $\mathcal{Y}_1(\vec{p}_4 - \vec{p}_5)$, since the quark and antiquark are in a relative P wave. The operator γ_0^{eff} of Eq. (13) is an effective pair-creation strength [28, 30, 33, 45, 46], defined as

$$\gamma_0^{\text{eff}} = \frac{m_n}{m_i} \gamma_0, \quad (14)$$

with $i = n$ (i.e. u or d) or s (see Table II).

Parameter	Value U(7)	Value hQM
γ_0	14.3	13.319
α_b	2.99 GeV $^{-1}$	2.758 GeV $^{-1}$
α_m	2.38 GeV $^{-1}$	2.454 GeV $^{-1}$
α_d	0.52 GeV $^{-1}$	0
m_n	0.33 GeV	
m_s	0.55 GeV	

TABLE II: Pair-creation model parameters used in the calculations [33]. In the second column are given the parameters used in the calculations with the relativistic phase space factor of Eq. (11) for U(7) model, while in the third column those for hQM. The values of the constituent quark masses m_n ($n = u, d$) and m_s are taken from Refs. [28, 30, 45].

Finally, the select results from our study of Ref. [33], obtained with the values of the model parameters of Table II (second column) and the relativistic phase space factor of Eq. (11), are reported in Table I.

V. DISCUSSION AND CONCLUSIONS

In this contribution, we discussed some recent results for the open-flavor strong decay widths of **** nucleon resonances within a modified 3P_0 pair-creation model [33]. The baryon spectrum, we needed in our calculation, was predicted within the U(7) algebraic model [35] and the hQM [36], developed by Giannini and Santopinto.

One can observe that the results of Table I for **** nucleon resonances from Ref. [33] are quite similar for $N\pi$ and $\Delta\pi$ channels, in both the fits we did for the hQM and U(7) model cases. But it is worthwhile noticing that the parameters of the 3P_0 model are quite different, see Table II. On the contrary, in the case of the $\eta\pi$ channels the predictions are different in the hQM and U(7) model.

The possibility of using different models to extract the baryon spectrum helps to understand differences between different types of quark models. Another step towards a deeper understanding of this type of processes could be an extension of the quark model to include the continuum components in the baryon wave function. Thus, in a subsequent paper we will focus on threshold effects and the decays of states close to open and hidden-flavor decay thresholds. This procedure will not only have an effect on the widths, but also on the mass values [47].

Acknowledgments

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